Probing lepton flavour violating ALPs at $\mu^+\mu^+$ and μ^+e^- colliders

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with L. Calibbi, T. Li, Y. Yang,

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Axion-like particles

- ALPs pseudo Nambu-Goldstone bosons (PNGBs), that arise from the spontaneous breaking of a global U(1) symmetry. [See talk by L. Calibbi]
- Here we focus on **lepton-flavour-violating (LFV) ALPs** with generic dim 5 interaction :

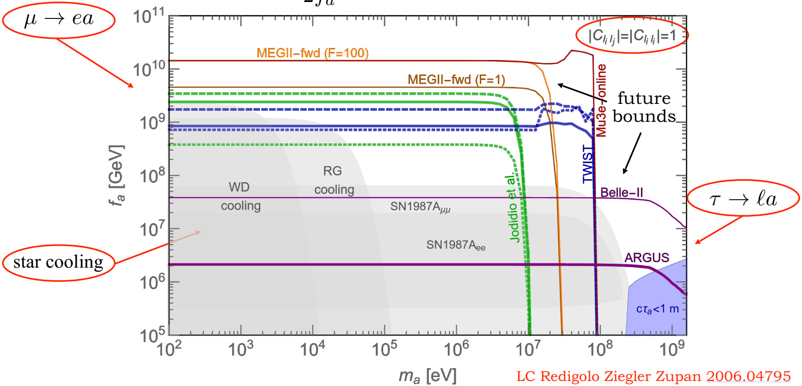
$$\mathcal{L}_{a\ell\ell} \supset \sum_i \frac{\partial_\mu a}{2f_a}\,\bar{\ell}_i C^A_{\ell_i\ell_i}\gamma^\mu\gamma_5\ell_i + \sum_{i\neq j}\frac{\partial_\mu a}{2f_a}\,\bar{\ell}_i\gamma^\mu\left(C^V_{\ell_i\ell_j} + C^A_{\ell_i\ell_j}\gamma_5\right)\ell_j\,,$$

  f_a = scale of $U(1)$ breaking.
- LFV couplings may arise naturally or at 1-loop level.
- We introduce a mass term $\frac{1}{2}m_a a^2$ that arises from explicit breaking of the $U(1)$ symmetry and treat m_a as a free parameter.

Current status of LFV ALPs

Lepton-flavour-violating invisible ALPs

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2 f_a} \bar{f}_i \gamma^\mu (C^V_{f_i f_j} + C^A_{f_i f_j} \gamma_5) f_j$$



LC Redigolo Ziegler Zupan 2006.04795

Decays mediated by dim-5 operators: much larger NP scales can be reached than $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conv. (from dim-6 ops, NP scale reach ~10^7–10^8GeV)

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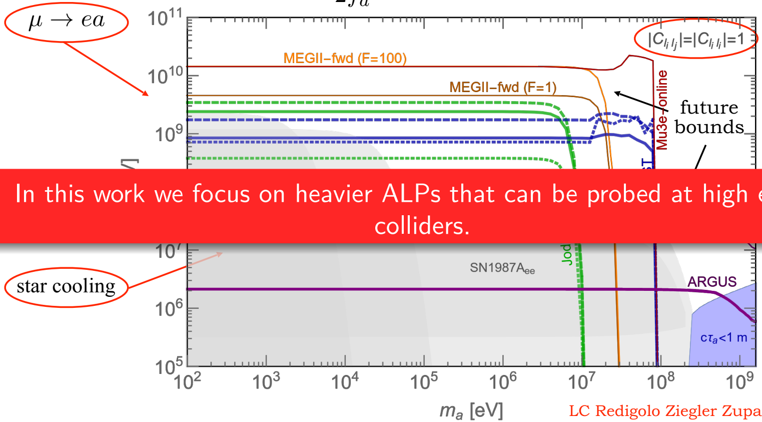

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In this work we focus on heavier ALPs that can be probed at high energy colliders.

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ALPs at muon experiments Lorenzo Calibbi (Nankai)

μTRISTAN proposal : $\mu^+\mu^+$ and μ^+e^- colliders

PTEP

Prog. Theor. Exp. Phys. **2022** 053B02(16 pages)
DOI: 10.1093/ptep/ptac059

μTRISTAN

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- The idea is to cool and focus μ^+ beams, a technology developed at JPARC [Abe et al., 1901.03047]
- The μ^+ beams could be accelerated up to 1 TeV and made to collide with :

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30 GeV e^- beam

→ "Higgs factory" with $\sqrt{s} \simeq 346$ GeV

→ Expected integrated luminosity $\mathcal{L} = 1$ ab^{-1}

OR

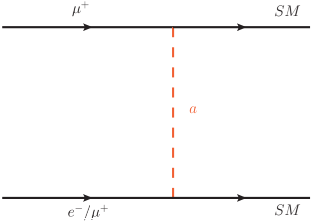
1 TeV μ^+ beam

→ "Discovery machine" with $\sqrt{s} = 2$ TeV

→ Expected integrated luminosity $\mathcal{L} = 100$ fb^{-1}

ALP Processes at μTRISTAN

ALP mediation



e.g, $\mu^+\mu^+ \to \ell^+\ell^+, \gamma\gamma$,
$e^-\mu^+ \to \ell^+\ell^{'-}$
$\sigma \propto 1/f_a^4$

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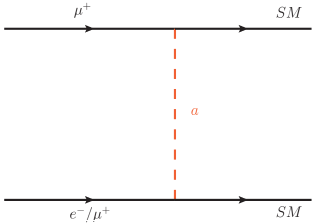

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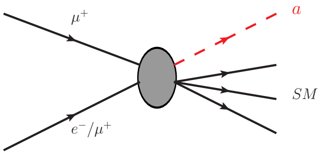
ALP production



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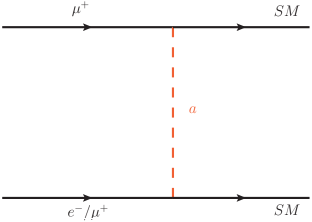

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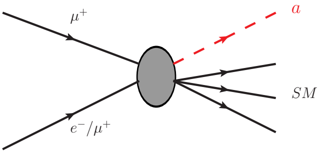

e.g, $\mu^+\mu^+ \to \ell^+\ell^{(\prime)+}a$,
$e^-\mu^+ \to \ell^+\ell^{'-}a, a\gamma, aZ$
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We focus on the following modes as a way to probe LFV ALP couplings :

- $C^{A,V}_{e\mu}$: $e^-\mu^+ \to a\gamma$;
- $C^{A,V}_{\mu\tau}$: $e^-\mu^+ \to e^-\tau^+a$ and $\mu^+\mu^+ \to \mu^+\tau^+a$;
- $C^{A,V}_{e\tau}$: $e^-\mu^+ \to \tau^-\mu^+a$.

Event analysis

- Signal and background events are generated using MADGRAPH, PYTHIA, and MADSPIN.
- Detector response is simulated using DELPHES.
- Resulting events are analysed using ROOT.
- We apply the default basic generator-level cuts on the final-state photons or charged leptons in MADGRAPH.
- Statistical significance is defined as

$$\mathcal{S} = \frac{N_{\rm S}}{\sqrt{N_{\rm S} + N_{\rm B}}} \, , \quad N_{\rm S(B)} = \sigma_{\rm S(B)} \times \varepsilon_{\rm S(B)} \times \mathcal{L} \, ,$$

- Signal efficiency : $\varepsilon_S \equiv \varepsilon_{\rm sel} \times \varepsilon_{\rm cut}$

↙ selection efficiency

↓ Includes geometric acceptance of detector and particle id probabilities

↘ signal acceptance after cuts.

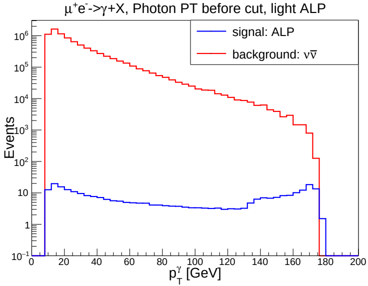
- Finally, we show the expected 95% CL exclusion potential of μTRISTAN.

Process 1. $e^-\mu^+ \to a\gamma$

- In presence of lepton flavour violating (LFV) coupling $C^{V,A}_{e\mu}$ only :

A. Light ALPs : $m_a < m_e + m_\mu$:

Signal : $e^-\mu^+ \to \gamma + \text{Invisible ALP}$
SM Background : $e^-\mu^+ \to \gamma + \nu_e\bar{\nu}_\mu$, quite significant!



B. Heavy ALPs : $m_a > m_e + m_\mu$:

Signal : $e^-\mu^+ \to \gamma + a\,(\to e^+\mu^-)$
SM Background : $e^-\mu^+ \to \gamma\nu_e\bar{\nu}_\mu W^-(\to \mu^-\bar{\nu}_\mu)W^+(\to e^+\nu_e)$, but negligibly small!

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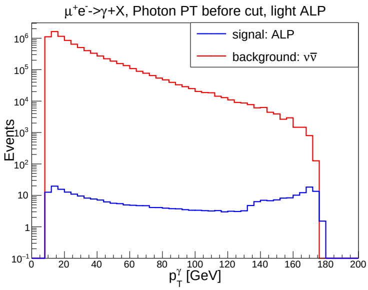

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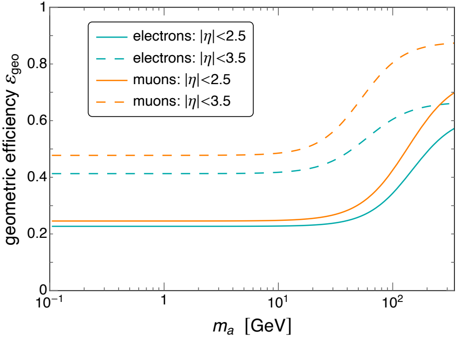
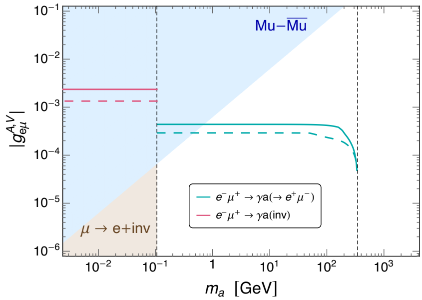
- If lepton flavour conserving (LFC) couplings are also open, then ALPs can further decay to $e^+e^-, \mu^+\mu^-$ if kinematically allowed.

Selection efficiency

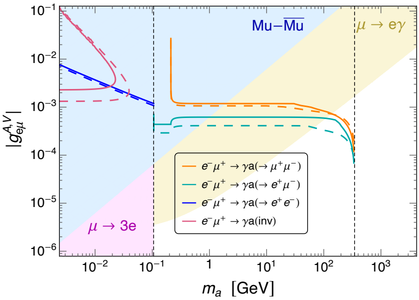
- Due to the asymmetric beam configuration ($E_e = 30$ GeV, $E_\mu = 1$ TeV), decay products highly boosted along the muon beam direction, with a very large pseudorapidity $|\eta|$.
- A substantial proportion of signal events is lost affecting signal efficiency.



Preliminary Results : $e^-\mu^+ \to a\gamma$



$C_{e\mu}^{V,A} = 1$ only



$C_{e\mu}^{V,A} = C_{ee}^{A} = C_{\mu\mu}^{A} = 1$

$$g_{\ell_i\ell_j}^{V,A} \approx m_{\ell_j}\frac{C_{\ell_i\ell_j}^{V,A}}{2f_a}\ (i<j), \quad g_{\ell_i\ell_i}^{A} = m_{\ell_i}\frac{C_{\ell_i\ell_i}^{A}}{f_a}$$

———— : $|\eta| < 2.5$

– – – – : $|\eta| < 3.5$

Process 2. ALP produced through LFV τ interactions

- Production cross-sections enhanced by the tau-mass.
- For τ identification, we use the hadronic/leptonic decay of τ.
- **Light ALPs** : eg, $m_a = 0.01$ GeV

	Signal	σ_S [fb]	Background	σ_B [fb]
$C_{\mu\tau}$	$\mu^+\mu^+ \to \mu^+\tau^+ a$, τ as jet	0.25	$\mu^+\mu^+ \to \mu^+\tau^+\bar{\nu}_\mu\nu_\tau$, τ as jet	180
	$e^-\mu^+ \to e^-\tau^+ a$, τ as jet	1.4	$e^-\mu^+ \to e^-\tau^+\bar{\nu}_\mu\nu_\tau$, τ as jet	24
$C_{e\tau}$	$e^-\mu^+ \to \tau^-\mu^+ a$, τ as jet	0.038	$e^-\mu^+ \to \tau^-\mu^+\bar{\nu}_\tau\nu_e$, τ as jet	4.8

$\to$ Background cross-section is huge.

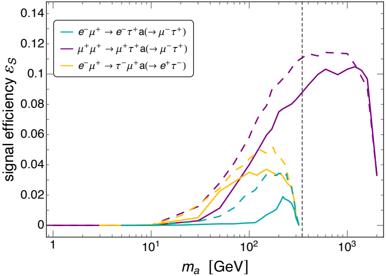
$\to$ Collider constraints not competitive compared to constraints from LFV τ decays.

- **Heavy ALPs** : eg, $m_a = 10$ GeV

	Signal	σ_S [fb]	Background	σ_B [fb]
$C_{\mu\tau}$	$\mu^+\mu^+ \to \mu^+\tau^+ a$, $a \to \tau^+\mu^-$	0.14	$\mu^+\mu^+ \to W^+W^+Z\bar{\nu}_\mu\bar{\nu}_\mu$, $W \to \tau\nu_\tau$, $Z \to \mu^+\mu^-$	6×10^{-4}
	$e^-\mu^+ \to e^-\tau^+ a$, $a \to \tau^+\mu^-$	0.93	$e^-\mu^+ \to \nu_e\bar{\nu}_\mu + 4W$, $W \to \ell\nu_\ell$	9×10^{-17}
$C_{e\tau}$	$e^-\mu^+ \to \tau^-\mu^+ a$, $a \to \tau^- e^+$	0.017	$e^-\mu^+ \to \nu_e\bar{\nu}_\mu + 4W$, $W \to \ell\nu_\ell$	9×10^{-17}

$\to$ Negligible background compared to the signal.

Preliminary results



For hadronic taus in final state

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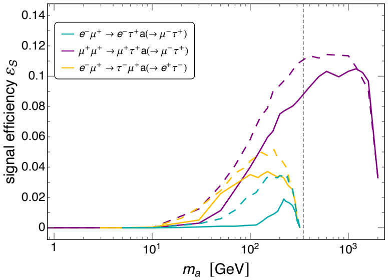

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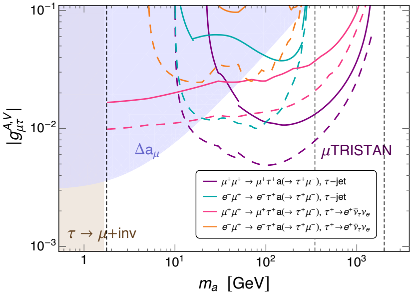

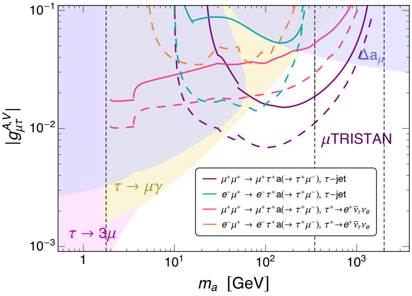

Summary

- We study the potential of ALP searches at proposed $e^-\mu^+$ and $\mu^+\mu^+$ colliders.
- The LFV interactions of heavier ALPs, for which the decays $\ell_i \to \ell_j a$ are kinematically forbidden, are comparatively poorly constrained.
- We highlight some distinctive signatures virtually affected by no (irreducible) SM background (BG).
- We do a detailed sensitivity study for both the signal and background.
- We obtain 95% C.L. on $g_{\ell_i\ell_j} \gtrsim 10^{-4}$ for $1\ \mathrm{GeV} < m_a \lesssim 1\ \mathrm{TeV}$.

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THANK YOU!!